2001

Entropy Generation Method to Quantify Thermal Comfort

S. C. Boregowda

S. N. Tiwari
Old Dominion University

S. K. Chaturvedi
Old Dominion University, schaturv@odu.edu

Original Publication Citation

Boregowda, S. C., Tiwari, S. N., & Chaturvedi, S. K. (2001). Entropy generation method to quantify thermal comfort. *Journal of Human Performance in Extreme Environments, 6*(1), 40-45.

Entropy Generation Method to Quantify Thermal Comfort

S. C. Boregowda[1]Center for Research in Security Prices,
University of Chicago Graduate School of Business
725 S. Wells, Suite 800, Chicago, IL 60607

S. N. Tiwari[2] and **S. K. Chaturvedi**[3] Department of Mechanical Engineering, Old Dominion University, Norfolk, Virginia 23529

Summary

The present paper presents a thermodynamic approach to assess the quality of human-thermal environment interaction and quantify thermal comfort. The approach involves development of entropy generation term by applying second law of thermodynamics to the combined human-environment system. The entropy generation term combines both human thermal physiological responses and thermal environmental variables to provide an objective measure of thermal comfort. The original concepts and definitions form the basis for establishing the mathematical relationship between thermal comfort and entropy generation term. As a result of logic and deterministic approach, an Objective Thermal Comfort Index (OTCI) is defined and established as a function of entropy generation. In order to verify the entropy-based thermal comfort model, human thermal physiological responses due to changes in ambient conditions are simulated using a well established and validated human thermal model developed at the Institute of Environmental Research of Kansas State University (KSU). The finite element based KSU human thermal computer model is being utilized as a "Computational Environmental Chamber" to conduct series of simulations to examine the human thermal responses to different environmental conditions. The output from the simulation, which include human thermal responses and input data consisting of environmental conditions are fed into the thermal comfort model. Continuous monitoring of thermal comfort in comfortable and extreme environmental conditions is demonstrated. The Objective Thermal Comfort values obtained from the entropy-based model are validated against regression based Predicted Mean Vote (PMV) values. Using the corresponding air temperatures and vapor pressures that were used in the computer simulation in the regression equation generates the PMV values. The preliminary results indicate that the OTCI and PMV values correlate well under ideal conditions. However, an experimental study is needed in the future to fully establish the validity of the OTCI formula and the model. One of the practical applications of this index is that could it be integrated in thermal control systems to develop human-centered environmental control systems for potential use in aircraft, mass transit vehicles, intelligent building systems, and space vehicles.

1.0 Introduction

During the past five decades, numerous studies have been conducted to understand and examine the thermal aspects of the environmental condition and its effects on human thermal physiology. With regard to academic interest, it poses some challenging problems that require the expertise of researchers from different fields such as engineering, psychology, physiology, and medicine. In many cases, one specialist does not know what the other specialist is doing. The need to bridge this gap between the academic disciplines is one of the motivating factors behind this work.

Numerous researchers have established the fact that thermal com-

http://dx.doi.org/10.7771/2327-2937.1015

fort influences human attention, vigilance, and mental performance in one-way or the other (Chase & Karwowski, 2000; Hancock & Pierce, 1984). Thermal comfort is influenced by environmental and physical factors such as air temperature, humidity, air movement, physical activity, and clothing. According to ASHRAE Standard (Fanger, 1970), human thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment." Although thermal comfort is defined as a condition of mind, it could be expressed in terms of physiological responses to changes in the thermal environment.

A thermal stress index is traditionally defined as one that combines two or more parameters, such as air temperature, mean radiant temperature, relative humidity, and air velocity into a single variable (ASHRAE, 1993). Thermal or environmental indices may be classified according to how they are developed. Rational indices are based on the theoretical concepts presented earlier. Empirical indices are based on measurements with subjects or on simplified relationships that do not necessarily follow any theory. Indices may also be classified according to their application, generally either heat stress or cold stress. Some of the widely used indices are: Effective Temperature, Heat Stress Index, Wet-Bulb Globe Temperature, Wind Chill Index, and PMV. One of the major limitations of these indices is that they are difficult to use and implement in an operational or real-time environments. The present study is dedicated to the development of a simple thermal comfort index that could be integrated in operational environments.

2.0 Methodology

The human thermal physiological responses to changes in thermal environment are simulated using a computer model (Fu, 1995; Smith, 1991). The inputs (thermal environmental properties) and the outputs (physiological responses) are fed into the entropy-based thermal comfort index model. In this section, the human thermal model is briefly described followed by the mathematical derivation of thermal comfort index.

Human Thermal Model

The human thermal model developed by Smith (1991) and Fu (1995) using finite element method and modified by Boregowda (1998) is used to numerically simulate human thermal physiological responses in a transient non-uniform thermal environment. The model consists of three interactive systems, namely: (a) Passive System, which includes the body tissues, internal organs, circulatory system, and respiratory system; (b) Control System, which represents the thermal control functions of the body; and (c) Clothing System, that takes into account the thermal functions of the clothing. The interactive systems are modeled using a set of governing energy (parabolic differential) equations. The differential equations are solved numerically subject to appropriate initial and boundary conditions to simulate human thermal responses to changes in thermal environment.

Thermal Comfort Index Model

The ASHRAE (Fanger, 1970) definition of thermal comfort is extended to include physiological reaction to changes in the thermal environment and defined under Postulate I as follows:

Postulate I. *Thermal comfort is defined as a condition of mind that expresses satisfaction with the thermal environment and is reflected in physiological reaction to corresponding changes in the thermal environment except in cases of individuals with rare diseases and those who have achieved voluntary self-regulation of their physiological functioning.*

From the laws of psychophysics, the following logic is established (Flach and Warren, 1995; Fechner, 1966):

Psych = f {Physical} (1)

According to ASHRAE standard (Fanger, 1970), thermal comfort is a condition of mind that leads us to the understanding that thermal comfort occurs in psychological domain. Thus,

Thermal Comfort = Psych = f {Physical} (2)

The physical system is a combination of human body and thermal environment. Thus, thermal comfort is defined using a thermodynamic function in the following manner.

Thermal Comfort = H x f {Physiological Responses, Thermal Environmental Variables} (3)

Where H = Non-dimensional Human Coefficient that takes into account the variation in individual responses to thermal environment. It depends on age, sex, race, and other related factors. The value of H was taken to be equal to 1.0 with the assumption of a "Standard Human" in the present simulation study. However, in experimental studies of the future, the researcher will have to make a decision to assign the suitable value based on the situation. For example, the value of H would be different in tropical and warmer regions of the world where people are used to working in hot and humid climatic conditions. For example, Europeans living in Africa for a long-time get used to the hot climates and respond differently from their counterparts in Europe. The coefficient "H" provides a link between physiology and behavior. Although, we might be composed of the same anatomy, why do we respond to the same thermal conditions differently? How do we infer behavior from physiology and vice versa? Is behavior and physiology, one and the same? These are all questions facing the scientific community and will require researchers from different fields to come to consensus on this issue.

After having established the fact that thermal comfort is a function of the physical system consisting of human body and thermal environment, the next step is to find a suitable thermodynamic quantity that would represent this physical system. In this study, the entropy generation (S_{gen}) was discovered to be a significant thermodynamic quantity that combines both physiological and environmental variables. The concept of entropy has been introduced in human physiology by Aoki (1989, 1990) with the help of experimental data. According to Aoki, the entropy concept is as important as the concept of energy from the thermodynamic standpoint. All systems including the human thermal system obey the second law of thermodynamics. Entropy is a measure of disorder or chaos in any system in the universe (Callen, 1985). The entropy generation provides a global measure of violent motions and reactions occurring in nature. Hence, the entropy generation in the human thermal system shows the extent of activeness of (1) heat flows and (2) motions and reactions of substances within the body as a whole (Aoki, 1989, 1990). Therefore, the entropy generation is a significant eco-physiological quantity that characterizes the combined human-thermal environment system from thermodynamic and holistic viewpoints. Thus, entropy generation (S_{gen}, J/sec/K) is expressed mathematically as follows:

S_{gen} = f {Physiological Responses, Thermal Environmental Variables} (4)
Substituting Eq. (4) in (3), we get the expression for thermal comfort, which is:
Thermal Comfort = H x f {Entropy Generation (S_{gen})} (5)

In order to calculate entropy generation, one needs to identify the physical variables that are categorized as follows:

<u>(i) Thermal Environmental Variables</u>
Thermal resistance of the clothing (I_{cl}, clo)
Air temperature (T_{air}, K)
Relative humidity (RH, %)
Activity Level or metabolic heat generation (M, Joules/hr-cm^2)

<u>(ii) Physiological Responses</u>
Skin temperature (T_{skin}, K)
Core temperature (T_{core}, K)
Convective heat loss from the skin surface (E_{CNV}, Joules/sec)
Radiative heat loss from the skin surface (E_{RAD}, Joules/sec)
Evaporative heat loss from the skin surface (E_{EVAP}, Joules/sec)
Convective heat loss due to respiration (E_{RES_CNV}, Joules/sec)
Evaporative heat loss due to respiration (E_{RES_EVAP}, Joules/sec)

The entropy generation term is derived from the second law of thermodynamics as (Nicolis and Prigogine, 1977). However, entropy generation (S_{gen}, J/sec/K) is found to be a function of both environmental variables and human thermal responses (Boregowda, 1998), i.e.,

$S_{gen} = f\{T_{skin}, T_{core}, E_{CNV}, E_{RAD}, E_{EVAP}, E_{RES\_CNV}, E_{RES\_EVAP}, M, I_{cl}, T_{air}, RH\}$ (6)

The detailed steps to reduce the variables of Eq. (6) shown by Boregowda (1998) and the derivation of entropy generation term and Objective Thermal Comfort Index are described in Appendix.

The OTCI is defined under Postulate II as follows:

Postulate II. *The percentage deviation in the value of entropy generation from the comfort or equilibrium condition provides a quantitative measure of the level of satisfaction expressed by the mind with thermal environment and is termed as Objective Thermal Comfort Index (OTCI).*

The Objective Thermal Comfort Index is mathematically expressed as
$OTCI = H \times [1.0 - (S_{gen})_{act}/(S_{gen})_{com}] \times 100$ (7)
where subscripts "act" and "com" stand for actual and comfort values respectively.

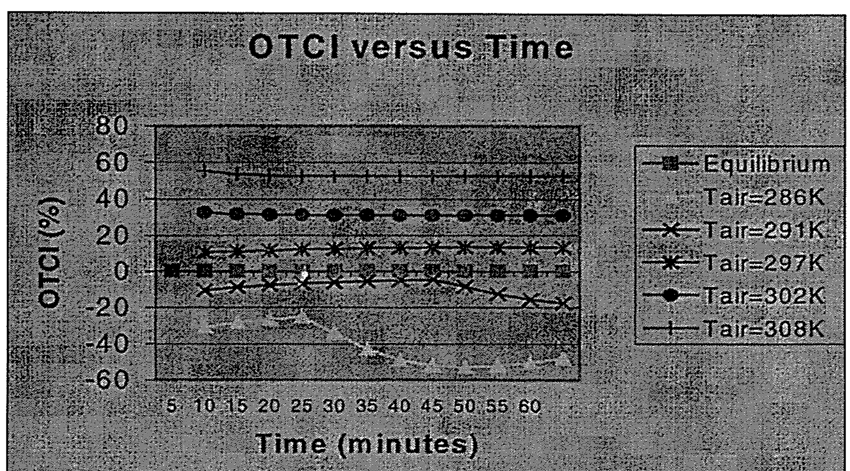
The mathematical and thermodynamic details pertaining to the formulation of OTCI are clearly presented in the Appendix. The OTCI provides a measurement standard that takes into account both environmental variables and human thermal responses.

3.0 Results
The simulation data obtained from the computer model developed by Fu (1995) and Smith (1991) are fed into the entropy-based thermal comfort model, which in turn provides quantitative measure of thermal comfort. The continuous monitoring of thermal comfort level in both comfortable and extreme environmental conditions is demonstrated. The OTCI is validated by conducting correlation analysis with the PMV data obtained from a large-scale experimental study.

3.1 Thermal Comfort Level Monitoring in Comfortable Environmental Conditions
The computer simulations were conducted for a period of one hour for a clothed human in comfortable environmental conditions. The effects of varying air temperatures for different relative humidities on human thermal comfort level are examined. Fig. 1 shows the human thermal response in terms of OTCI to different air temperatures ranging from 286K to 308K for a given relative humidity of 50%, sedentary activity (M = 21 Joules/hr-cm^2), and medium clothing ensemble (I_{cl} = 0.69 clo).

Figure 1. Effect of Air Temperatures on Thermal Comfort Level for 50% RH

3.2 Thermal Comfort Level Monitoring in Extreme Hot and Cold Environments



Simulations were conducted for a period of one hour for a sedentary clothed human in extreme ambient conditions. The effects of extreme cold (273.15K) and hot (316.48K) air temperatures for 10% relative humidity are examined.

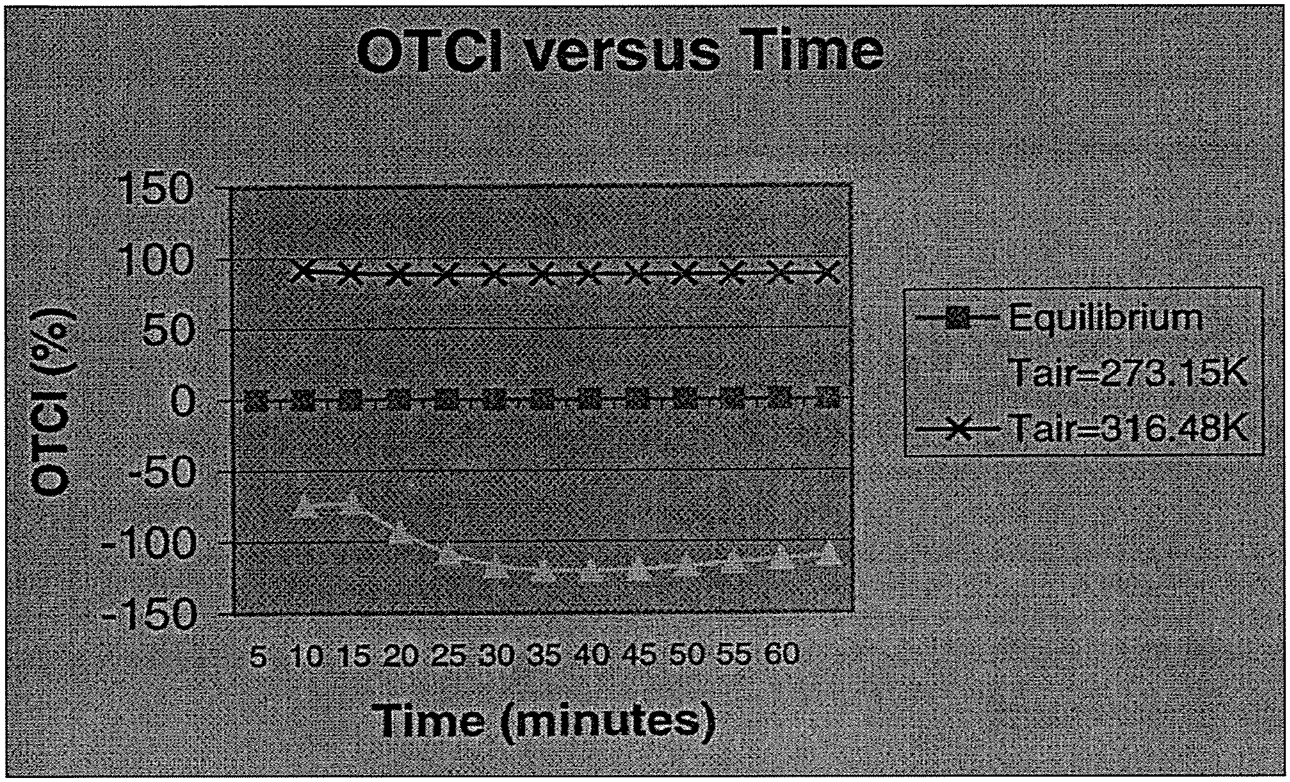


Figure 2. Thermal Comfort in Extreme Air Temperatures for 10% RH

3.3 Validation of Objective Thermal Comfort Index (OTCI)

The OTCI is validated by comparing with subjective responses of the human subjects who were exposed to the similar environmental conditions. Large-scale experimental studies conducted by Rohles and Nevins (1971) and Rohles (1973) on 1600 college-age students have revealed statistical correlations between comfort level, temperature, sex, and length of exposure. The regression equation used in this validation is obtained from ASHRAE (1993). This equation is as follows:

$$PMV = 0.245\,(T_{air}) + 0.248\,(P_{vap}) - 6.475 \quad (8)$$

Where,

T_{air} = Air temperature (°C) = Mean radiant temperature (T_{mrt},°C)

P_{vap} = Vapor pressure (kPa)

This equation is valid for both adult men and women subjects with sedentary activity (M = 21 Joules/hr-cm^2) and wearing medium clothing (approximately, I_{cl} = 0.50 clo), and exposed for one hour to air velocities less than 0.2 m/sec. The thermal sensation scale used in this equation is referred to as the ASHRAE thermal sensation scale and is the same as the PMV scale developed by Fanger (1970). This scale is as follows:

Hot Warm Slightly Warm Neutral Slightly Cool Cool Cold

_+3_______+2________+1__________0___________-1_________-2_______-3_

In the actual experiments (Fanger, 1970), the subjects were asked to vote at every thirty-minute interval on their thermal sensation of comfort level and their mean votes and their mean votes were considered for assessing the thermal environment. In order to be consistent with the experimental studies, OTCI values at 30th and 60th minutes were chosen and their mean value was taken for comparison with the PMV obtained from the regression equation.

Table 1. Correlation between OTCI and PMV in Comfort Conditions

	RH = 30%		RH = 50%		RH = 70%	
Tair (K)	OTCI (%)	PMV	OTCI (%)	PMV	OTCI (%)	PMV
285.93	-45.4990	-3.2328	-45.4374	-3.1587	-44.9166	-3.0847
291.48	-11.8702	-1.8259	-11.4687	-1.7204	-10.9505	-1.6149
297.04	13.7436	-0.3999	13.1414	-0.2518	12.6456	-0.1038
302.59	31.3358	1.0477	31.0026	1.2493	30.6569	1.4540
308.15	52.9799	2.5187	52.5688	2.7979	52.0788	3.0770
Corr. Coeff	0.9913		0.9906		0.9900	

Table 2. Correlation between OTCI and PMV in Extreme Condition

Tair (K)	RH = 10%		RH = 90%	
	OTCI (%)	PMV	OTCI (%)	PMV
273.15	-115.3115	-6.4598	-114.9475	-6.3386
316.48	88.4137	4.3605	74.7081	6.1173
Corr. Coeff	1.00		1.00	

4.0 Discussion

In comfortable conditions, it is observed from Figure 1 that there is a significant deviation in thermal comfort from the equilibrium condition. Cool air temperature (286K) produces deviation in the negative direction, starting from approximately –30% to about –47% towards the end of the 60th minute. As the air temperature is increased to 291K, the deviation from the equilibrium condition reduces starting from about –10% to –18%. As the air temperature continues to increase, thermal discomfort shifts from the equilibrium in the positive direction. It is concluded that warmer air temperatures produce deviations in positive direction, while the cooler air temperatures produce shifts in the negative direction from the thermal equilibrium of the body. Also, it is noticed that OTCI indicates a sudden change in thermal stress level at 25th and 45th minutes for air temperatures 286K and 291K, respectively. This is mainly attributed to the onset of heat production due to shivering, which contributes to the increase of entropy production.

In case of extreme environmental conditions, it is observed from Fig. 2 that for a 10% RH, the deviations from the thermal equilibrium are large indicating thermal discomfort of extreme cold and hot for 273.15K and 316.48K air temperatures respectively. Further, it is noticed that there is an onset of shivering at the 10th minute, which is seen in both Fig. 2 for 273.15K air temperature.

The OTCI is validated against the values of PMV for both comfortable and extreme conditions. In case of comfortable conditions, Table 1 shows that there is a significant correlation between OTCI and PMV, which is expressed quantitatively with the help of coefficient of correlation (or Pearson Correlation Coefficient). The values of coefficient were found to be equal to 0.9913, 0.9906, and 0.9900 for 30%, 50%, and 70% relative humidities respectively for air temperatures ranging from 286K to 308K. The main advantage of using OTCI lies in its simplicity and objectivity supported by the strong basis of second law of thermodynamics. With regard to extreme conditions, Table 2 shows that the value of correlation coefficients equal +1.0 for both 10% and 90% relative humidities for 273.15K and 316.48K air temperatures respectively. The value of correlation coefficient closer to +1 indicates that there is a linear variation between OTCI and PMV. It is established that there is a strong correlation between the OTCI and PMV based on the simulation results.

5.0 Conclusion

The results demonstrate the potential that OTCI could become a thermal comfort measurement standard in the future. The present study focused mainly on data from simulations and an established regression to show the correlation between OTCI and PMV or subjective thermal comfort. This was done mainly to overcome the cost of experimental studies and lack of resources on the part of the authors. In order to implement the OTCI in an operational environment, an experimental study needs to be conducted. With the availability of advanced non-invasive and non-contact sensors to measure human thermal physiological responses and the environmental variables, it would be possible to design and conduct an experimental study in the future. It is expressed in total confidence, that results from such a study would greatly benefit the scientific community to explore the relationship between human behavior and physiology from a thermodynamic perspective.

Acknowledgements

This work, in part, was supported by NASA Langley Research Center of Hampton, Virginia through a Cooperative Agreement Grant NCC1-254. The grant was monitored by Dr. Alan T. Pope. Authors express their special thanks to Dr. Byron W. Jones, Chair and Professor of Mechanical Engineering, Kansas State University for valuable suggestions and guidance.

References

Aoki, I., 1989, Entropy Flow and Production in the Human Body in Basal Condition, _Journal of Theoretical Biology,_ 141, 11 - 21.

Aoki, I., 1990, Effects of Exercise and Chills on Entropy Production in Human Body, _Journal of Theoretical Biology,_ 145, 421-428.

ASHRAE, 1993, _ASHRAE Handbook of Fundamentals,_ Chapter 8, Atlanta, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

Boregowda, S. C., 1998, _Thermodynamic Modeling and Analysis of Human Stress Responses,_ Published Ph.D Thesis, Old Dominion University, Norfolk, VA.

Callen, H. B., 1985, _Thermodynamic and An Introduction to Thermostatics,_ Second Edition, John Wiley & Sons, New York, 1985.

Chase, B., and Karwowski, W., 2000, Attention Allocation Under Thermal Stress, _Proceedings of the IEA 2000/HFES 2000 Congress,_ Vol. 5, 363-366.

Fanger, P. O., 1970, _Thermal Comfort,_ Second Edition, McGraw-Hill Book Company, New York.

Fechner, G., 1966, _Elements of Psychophysics,_ Holt, Rinehart, and Winston, New York.

Flach, J. M., and Warren, R., 1995, Active Psychophysics: The Relation Between Mind and What Matters, In Flach, J. M., Hancock, P. A., Caird, J., and Vicente, K. J. (Eds.), _Global Perspectives on the Ecology of Human Machine Systems, Vol. 1,_ Erlbaum Associates, Publishers, Hillsdale, NJ.

Fu, G., 1995, _A Transient, Three-Dimensional Mathematical Model_ *for Clothed Human.* Published h.D. Thesis, Kansas State University, Manhattan, Kansas.

Gagge, A. P., 1981, Rational Temperature Indices of Thermal Comfort, In Cena, K., and Clark, J. A. (Eds.), *Bioengineering, Thermal Physiology and Comfort,* Elsevier Scientific Publishing Company, Amsterdam, 1981, 79-98.

Hancock, P. A., and Pierce, J. O., 1984, Toward an Attentional Theory of Performance Under Stress: Evidence from Studies of Vigilance in Heat and Cold, In Mital, A., (Ed.), *Trends in Ergonomics/Human Factors I,* Elsevier Science Publishers, Inc., New York.

Nicolis, G., and Prigogine, I., 1977, *Self-Organization in Nonequilibrium Systems,* John Wiley & Sons, New York.

Rohles, F. H., Jr., 1973, The Revised Modal Comfort Envelope, *ASHRAE Transactions,* 79(2), 52 - 60.

Rohles, F. H., Jr., and Nevins, R. G., 1971, The Nature of Thermal Comfort for Sedentary Man, *ASHRAE Transactions,* 77(1), 239-251.

Smith, C. E., 1991, *A Transient Three-Dimensional Model of the Human Thermal System,* Published Ph.D. Thesis, Kansas State University, Manhattan, Kansas.

APPENDIX: Derivation of OTCI

Living organisms including human beings belong to the class of open systems. This is due to the fact that they have to continuously exchange energy and matter with the surroundings in order to maintain homeostasis, which is essential for the existence and support of life. Nicolis and Prigogine (1977) formulated an extended version of the second law of thermodynamics applicable to both closed and open systems.

Consider the entropy change dS during a time interval dt. The entropy change dS is decomposed into sum of two contributions as expressed:

$dS = dS_{flow} + dS_{gen}$ (A.1)

In the present study, Eq. (A.1) is modified as shown by Aoki (1989, 1990) as

$?S = S_{flow} + S_{gen}$ (A.2)

where

$?S$ = total entropy change

S_{flow} = net entropy flow

S_{gen} = entropy generation

From Eq. (A.2), the entropy generation in the human body is given by

$S_{gen} = ?S - S_{flow}$ (A.3)

where ?S = Total Heat Generation in the Body (?Q) / Core Temperature (T_{core})

$S_{flow} = S_{in} - \{S_{out} + S_{CNV} + S_{EVAP} + S_{RAD} + S_{CNV\_RES} + S_{EVAP\_RES})$ (A.4)

The terms S_{in} and S_{out} on the right side of Eq. (A.4) are given as follows:

$S_{in} = 2.05\ ?\ (T_{air})^3$ (A.5a)

$S_{out} = 2.05\ ?\ (T_{skin})^3$ (A.5b)

where ? = Stefan-Boltzmann constant = 5.67×10^{-8} J. m^{-2} sec^{-1} K^{-4}. The other terms in Eq. (A.4) related to heat losses are given as follows:

$S_{CNV} = E_{CNV} / T_{skin}$ (A.6a)

$S_{RAD} = E_{RAD} / T_{skin}$ (A.6b)

$S_{EVAP} = E_{EVAP} / T_{core}$ (A.6c)

$S_{CNV\_RES} = E_{CNV\_RES} / T_{skin}$ (A.6d)

$S_{EVAP\_RES} = E_{EVAP\_RES} / T_{core}$ (A.6e)

The entropy generation is calculated at the equilibrium or comfort condition at 50% RH and 75°F air temperature for nude body. Thus, any percentage deviation from the equilibrium or comfort entropy generation value indicates the amount of deviation in thermal comfort from ideal conditions. The OTCI is thus defined as

$OTCI = H \times [1.0 - (S_{gen})_{act}/(S_{gen})_{com}] \times 100$ (A.7)

Where,

subscript "act" = actual values

subscript "com" = comfort values

H = Non-dimensional Human Coefficient that takes into account the variation in individual responses to thermal environment. It depends on age, sex, race, and other related factors. The value of H was taken to be equal to 1.0 with the assumption of a "Standard Human" in the present simulation study.

1. *Quality Assurance Engineer, ASME (American Society of Mechanical Engineers) Member*

2. *Eminent Professor, AIAA (American Institute of Aeronautics & Astronautics) Fellow*

3. *Professor and Chairman, ASME Member*